

SOLAR NEUTRINOS AS HIGHLIGHT OF ASTROPARTICLE PHYSICS ¹

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ABSTRACT

Solar neutrinos are discussed in the light of the new data and of the recent progress in helioseismology. The most attention is given to the new status of Standard Solar Models due to seismically measured density and sound speed in the inner solar core. The elementary particle solutions to the Solar Neutrino Problem and their observational signatures are discussed .

1. INTRODUCTION

As everybody knows, the earth and sun were created for the sake of neutrino-oscillation experiment. The distance between them was chosen as vacuum oscillation length, the density inside the sun - to fit the MSW effect and the sun was prepared as an ideal pure ν_e -source. When all this was done, there were created Bruno Pontecorvo - to invent idea of neutrino oscillations, John Bahcall - to calculate the solar-neutrino flux, Ray Davis - to perform the first solar-neutrino experiment and all other solar-neutrino people to accomplish this difficult job. The last in this row was Maury Goodman - to cite silly jokes like this one in his neutrino news.

In this review I want to convince the readers, that the Solar Neutrino Problem (SNP) is not a vague astrophysical puzzle, but an elementary-physics problem - the first step beyond the Standard Model of EW interactions. The neutrino with the properties as in the Standard Model will be referred to as *standard neutrino*.

These years we are entering the new epoch in solar-neutrino physics.

1. It is characterized by the new detectors: SuperKamiokande (in operation) and SNO and Borexino, which will start to operate soon. These detectors will be able to discover the direct signatures of elementary particle solution to the SNP in a few years.
2. During last several years, the convincing model-independent arguments demonstrated that there is no astrophysical solution (nuclear physics included) to the SNP. Now we go much further. Helioseismic data confirm the Standard Solar Models (SSMs) with high precision at all radial distances at interest. The confidence to the SSMs is greatly strengthened and their serious revision looks now unrealistic. The interest is shifted from the model-independent analysis to the accuracy of the SSM predictions and especially to the fine details not essential for the prediction of neutrino fluxes.
3. The uncertainties in the cross-sections are now the dominant ones for the prediction of the solar-neutrino fluxes. The impressive progress exists here as well. In the LUNA experiment at Gran Sasso the cross-section of one of the most intriguing reactions, $^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p$, was measured at energy corresponding to maximum of the Gamow peak in the Sun. The famous speculations about solving or ameliorating the SNP due to increase of this cross-section at very low energy, have been now honorably buried. In the nearest future most of cross-sections relevant to the SMP will be measured in the LUNA experiment at very low energies.

The plan of my review is as follows. I will start with the good old-fashioned story about disfavouring (which is a good diplomatic equivalent for the word excluding) of astrophysical

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solution to the SNP. In section 3 I will describe the status of the SSMs in the light of helioseismic data. In the section 4 the status of nuclear-reaction cross-sections will be shortly reviewed. In sections 5 and 6 the elementary-particle solutions to the SNP will be discussed. For early detailed reviews see e.g. Bahcall 1989, Turck-Chieze et al 1993, Bowles and Gavrin 1993, Kirsten 1995 and Castellani et al 1997.

2. STATUS OF ASTROPHYSICAL SOLUTION TO SNP

The Solar Neutrino Problem (SNP) is a deficit of neutrino fluxes detected in all four solar-neutrino experiments (Suzuki 1997, Conner 1997, Hampel et al 1996, Abdurashitov et al 1997, Cleveland et al 1995). The data, as reported up to 1997, are listed in Table 1 and compared with calculations of Bahcall and Pinsonneault (1995) for the Standard Solar Model (SSM).

Table 1: The solar-neutrino data of 1997 compared with the SSM prediction , Bahcall and Pinnsonneault (1995)

	DATA	SSM [5]	DATA/SSM
GALLEX (SNU)	$69.7 \pm 6.7^{+3.9}_{-4.5}$	137	0.509 ± 0.059
SAGE (SNU)	$69 \pm 10^{+5}_{-7}$	137	0.504 ± 0.085
SUPERK ($10^6 \text{ cm}^{-2}\text{s}^{-1}$)	$2.44 \pm 0.06^{+0.25}_{-0.09}$	6.5	0.368 ± 0.026
HOMESTAKE (SNU)	$2.55 \pm 0.17 \pm 0.18$	9.3	0.274 ± 0.027

The solar neutrino spectrum is characterized by three most important components (see Table 2).

(i) The most energetic part of the spectrum is presented by boron neutrinos from ${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$ decay. The maximum energy of neutrinos in this spectrum is $E_{\nu, \max} \approx 14 \text{ MeV}$. Kamiokande and SuperKamiokande detect only boron neutrinos.

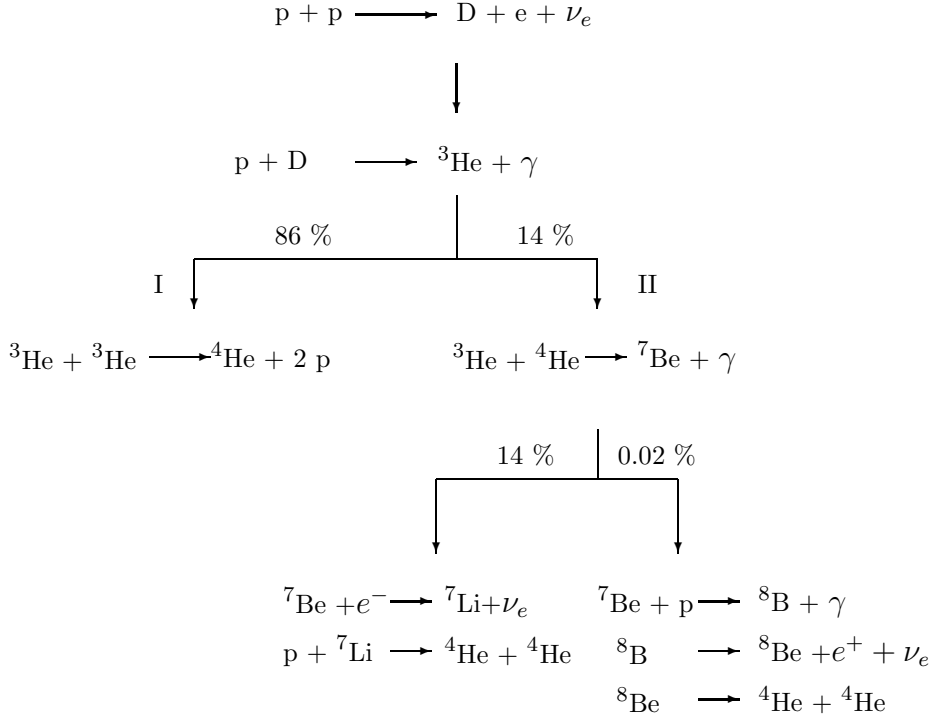
(ii) Beryllium neutrinos (${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$) are monoenergetic ($E_\nu = 0.862 \text{ MeV}$). Predicted flux of Be-neutrinos depends weakly on the solar model and is $(4.2-4.9) \cdot 10^9 \text{ cm}^{-2}\text{s}^{-1}$. Homestake detects both boron and beryllium neutrinos: ${}^8\text{B}$ -neutrinos provide about 80% of the total signal and ${}^7\text{Be}$ -neutrinos - about 13%

(iii) The low-energy part of the solar-neutrino spectrum is presented by pp - neutrinos ($p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$) with maximum energy $E_\nu^{\max} = 0.42 \text{ MeV}$. These neutrinos greatly outnumber the flux of other neutrinos ($6.1 \cdot 10^{10} \text{ cm}^{-2}\text{s}^{-1}$). The flux is determined practically only by solar luminosity and therefore is reliably predicted. GALLEX and SAGE measure mostly pp -neutrinos (about 50% of the total signal) with some contribution of ${}^7\text{Be}$ and ${}^8\text{B}$ neutrinos (about 28% and 12%, respectively).

From Table 1 one can see that the suppression factor, DATA/SSM, is less for Homestake than for SuperKamiokande detector. It is easy to understand that it creates a problem for nuclear/astrophysical solution to the SNP. Indeed, since the nuclear/astrophysical factors cannot change the shape of ${}^8\text{B}$ -neutrino spectrum, the suppression factor for boron neutrino signal in Homestake should be the same as in Kamiokande.

Of course ${}^7\text{Be}$ -neutrinos can be suppressed more strongly, but their contribution to the total signal in the Homestake detector is small ($\sim 13\%$). The incompatibility of the Homestake and

Table 2: Nuclear reactions in the Sun (pp-chain)



Kamiokande results was first recognized Bahcall and Bethe (1990): The contribution to the Homestake detector from B-neutrino flux only (taken from SuperKamiokande) is 2.71 SNU , and thus it is larger than the total Homestake signal (2.54 SNU).

It was demonstrated more accurately (e.g. Bludman et al 1993, Castellani et al 1993, Hata et al 1994, Berezhinsky 1994, Bahcall 1994, Kwong and Rosen 1994, Degl'Innocenti et al 1995, Castellani et al 1997) that comparison of Kamiokande and Homestake signals leave no place for ${}^7\text{Be}$ -neutrinos. Recently, this conclusion was confirmed by Hata and Langacker (1997) for the new SuperKamiokande flux.

Neutrino oscillations, e.g. $\nu_e \rightarrow \nu_\mu$, easily solves the Homestake/Kamiokande conflict. Each case of $\nu_e \rightarrow \nu_\mu$ conversion results in full disappearance of a signal in the Homestake detector ($\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e$), while in the Kamiokande detector it still exists due to $\nu_\mu + e \rightarrow \nu_\mu + e$ scattering. As a result the signal in Kamiokande should be stronger than in Homestake, as observed.

The deficit of beryllium neutrinos is seen not only from Homestake/SuperKamiokande conflict, but from comparison of the gallium signal with the signal from the SuperKamiokande or Homestake detectors (see the references cited above and recent calculations by Hata and Langacker 1997). Comparison of signals from any two detectors results in null beryllium-neutrino flux if neutrino is standard. However, one can notice that inclusion of the gallium signal, needs the solar-luminosity sum rule, i.e. connection between pp , Be and B neutrino fluxes and solar luminosity, which is valid only for stationary Sun.

Thus, the deficit of the beryllium-neutrino flux, i.e. the strong suppression of this flux to the value much smaller than predicted in the SSMs, looks as the most serious problem of the astrophysical solution to the SNP. This problem is naturally solved by elementary-particle solutions, where suppression of the fluxes is energy dependent. Beryllium neutrino flux will be directly measured by Borexino detector at Gran Sasso (Bellini 1996).

The second solar-neutrino problem is the deficit of the boron neutrinos. For the last 4-5 years we thought that with extreme and correlated uncertainties in pBe -cross-section and in the central temperature T_c this discrepancy can be eliminated. Now with the new data of SuperKamiokande and reduced errors in T_c due to helioseismic data (1.4%), the deficit of boron neutrinos is real again (Ricci et al 1997): the theoretical lower limit on boron neutrino flux is $2.2 - 3.5\sigma$ higher than the SuperKamiokande flux.

In the light of all known physics included and confirmation by seismic data, one cannot doubt any more, that the SSMs give *at least* the good approximation to the description of the sun. Then one can ask, whether there is a track from predictions of the SSMs to the observed solar neutrino flux, due to any (even unreasonable) change of the input parameters or due to ad hoc inclusion of the non-standard physics.

It is demonstrated that such track does not exist in case when these parameters are all nuclear cross-sections and central temperature T_c (Berezinsky et al 1996).

The failure of inclusion of non-standard physics is reviewed in the book by Bahcall (1989).

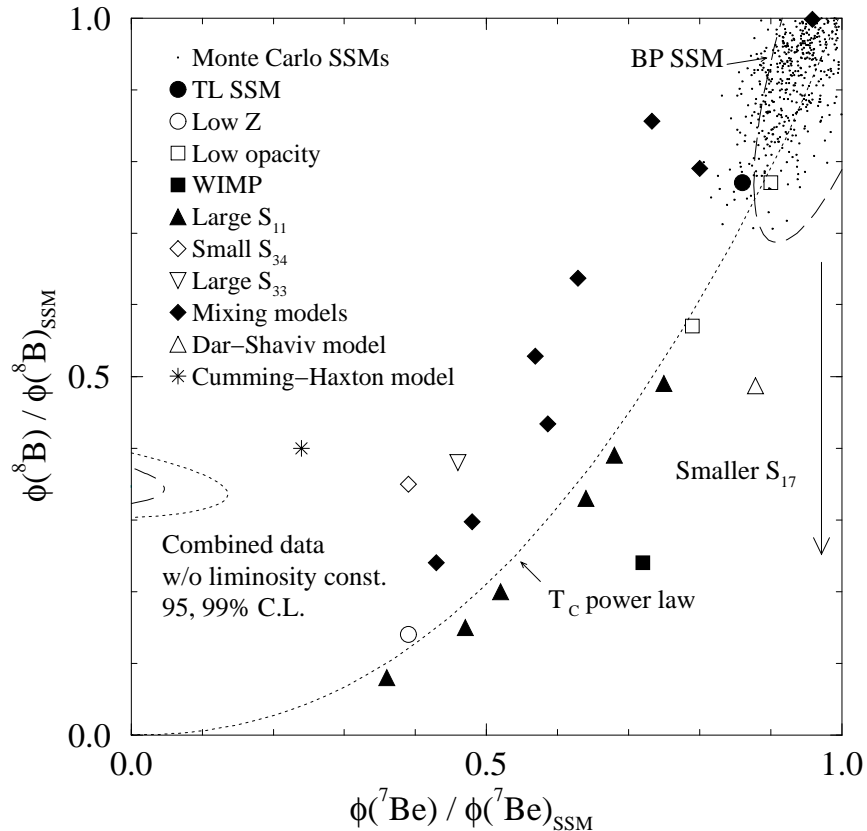


Fig.1. (from Hata and Langacker 1997). Is there a track from the region allowed by the SSMs (upper-right corner) to the region allowed by combined observational data (left corner)? The luminosity constraint is not imposed in calculations of the allowed region.

The modern status of this problem is clearly illustrated by Fig.1 from Hata and Langacker 1997 (note, that solar-luminosity sum rule is not imposed here). In accordance with calculations by Berezinsky et al 1996, one can see that no track leads from the SSMS models to the experimentally allowed region. The predictions of non-standard models are shown there as well. The Cumming-Haxton model (1996) reached the closest proximity to the allowed region. In this model the mixing in the inner core is *assumed*. Non-equilibrium ${}^3\text{He}$ coming to the center, produces ${}^4\text{He}$ through ${}^3\text{He} + {}^3\text{He}$, reducing thus production of boron and beryllium neutrinos. However, together with ${}^3\text{He}$ hydrogen gets in the inner core. It lowers molecular weight, increasing thus the sound speed. The calculations (Bahcall et al 1997) show that it exceeds the value allowed by seismic data.

3. HELIOSEISMOLOGY

As far as the SSMS are concerned we were very formal in the section 2, assuming they give only some approximation to the real picture inside the sun. In fact, these models are very well confirmed by the precise seismic measurements of sound speed and density profiles inside the sun.

Due to opposite forces of pressure and gravity, the sun can oscillate relative to its equilibrium configuration. The oscillations considered as small adiabatic perturbations, are described by usual set of equations for compressible selfgravitating gas. These equations give two solutions: the high-frequency pressure modes (p-modes) and low-frequency gravitational modes (g-modes). Till now only p-modes are observed with typical periods from several minutes to 1 hour. The acoustic waves (p-modes) propagate inside the sun non-radially. Approaching the deep interior, the wave is deflected from radial direction due increasing sound speed and finally is reflected (effectively due to gradient of sound speed). On its way back it is reflected again from outer layers due to pressure gradient. Thus acoustic waves are trapped in the solar cavity, forming the standing waves.

The photosphere of the sun is oscillating, forming a mosaic pattern, where various spots are moving with different velocities. These velocities can be measured due to e.g. Doppler shifts of optical lines. Thus the map of velocity field can be measured on the sun surface. The accuracy of velocity determination reaches 1 cm/s , though the typical one is $\sim 10\text{ cm/s}$.

The oscillation modes are characterized by the spherical harmonic numbers l , n , and corresponding frequency $\omega_{l,n}$. The dependence on the azimuthal number m is absent for spherically symmetric oscillations. The data consist of the large set of frequencies for the different numbers l and n . The frequencies are typically in the range between 1000 and 10000 μHz and the values of l are between $l = 0$ and ~ 1000 (see paper by M.Huber 1997 in these Proceedings for these and other details of helioseismology).

The tremendous accuracy of frequency measurements ($\sim 10^{-6}$) is a basis for precise determination of solar parameters in helioseismology.

The acoustic wave with given l is reflected at the distance r_t inside the sun (Christensen-Dalsgaard 1996a):

$$r_t = c(r_t) \sqrt{l(l+1)} / \omega_l, \quad (1)$$

where c is the adiabatic sound speed and ω_l is an angular frequency. As follows from Eq.(1), the modes with large l are reflected from large distance from the solar center, while modes with $l = 0$ penetrate into center.

To *invert* the measured frequency pattern $\omega_{n,l}^{obs}$ into some physical values inside the sun (e.g. sound speed c and density ρ radial profiles) one needs a solar model as an auxiliary tool. Using this model one calculates the difference of the frequencies $\delta\omega_{n,l} = \omega_{n,l}^{obs} - \omega_{n,l}^{mod}$. Using variational principal one can connect the variations of frequencies $\delta\omega_{n,l}$ with variations of the solar parameters $\delta c^2(r)$ and $\delta\rho(r)$ (see e.g. Gough and Thompson 1991, Christensen-Dalsgaard

1996a):

$$\frac{\delta\omega_{n,l}}{\omega_{n,l}} = \int_0^R dr K_{c^2}^{n,l}(r) \frac{\delta c^2(r)}{c^2(r)} + \int_0^R dr K_{\rho}^{n,l}(r) \frac{\delta\rho(r)}{\rho(r)} + \frac{F_{surf}(\omega_{n,l})}{I_{n,l}}, \quad (2)$$

where the last term in Eq.(2) is added to account for more complicated physics near the surface of the sun; $I_{n,l}$ are the calculated moments of inertia. The kernels of Eq.(2) are calculated in the reference (auxiliary) model. The mathematical inversion of Eq.(2) yields $c^2(r)$ and $\rho(r)$ in the solar interior. The success of this method depends on the choice of the reference model: the better is the model the smaller deflections δc^2 and $\delta\rho$ one obtains in the end. Apart from this method there is another one, where less precise asymptotic formulae are used, but which does not need an auxiliary model (for a review see Turck-Chieze 1993).

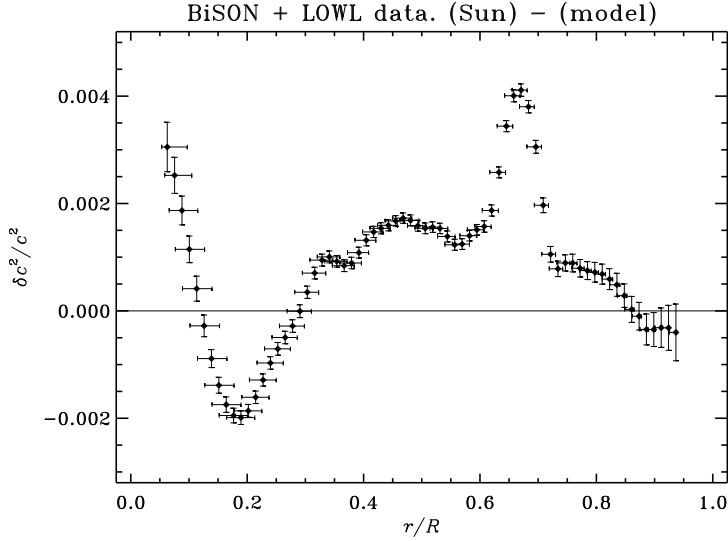


Fig.2 (from Christensen-Dalsgaard 1996b). The seismic sound speed profile compared with prediction of the reference model S of Christensen-Dalsgaard et al (1996c). Shown are deflections of sound speed squared from the calculated value.

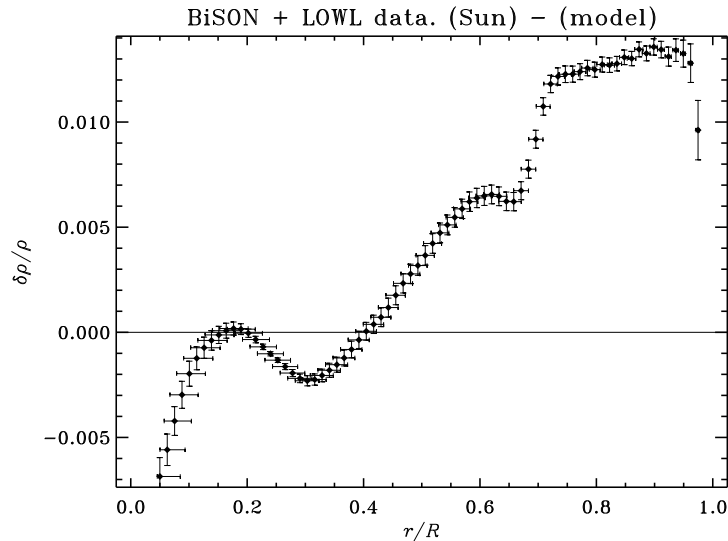


Fig.3 (from Christensen-Dalsgaard 1996b). The seismic density profile compared with prediction of the reference model S.

In Fig.2 and 3 the sound speed and density profiles, as presented by Christensen-Dalsgaard (1996b), are shown. As a reference model is used the standard model S of Christensen-Dalsgaard et al (1996c) with the diffusion of elements and settling included. The seismic data from the BiSON network and LOWL detector (SOHO satellite) are used. The horizontal line gives zero deflections from the SSM. Apart from two irregularities at $r/R \approx 0.7$ and $r/R \rightarrow 0$, where R is the solar radius, the agreement of c^2 (Fig.2) with the model calculated values is better than 0.2%. For the density (Fig.3) the agreement at distances $r/R < 0.7$ is better than 0.7%.

The most disturbing feature for the SNP in these results is increasing discrepancy between the SSM and observations in the inner core ($r/R \leq 0.1$): neutrino fluxes are produced mostly in the inner core.

A break-through in this problem was reached recently due to works by Dziembowski (1996) and Degl'Innocenti et al (1997a), and by Bahcall et al (1997).

As was explained above, only low l modes penetrate to the inner core. Dziembowski (1996) and Degl'Innocenti et al (1997a) used in their analysis 33 modes with $0 \leq l \leq 2$ and another 20 modes in the range of l between 5 and 13. The new method of inversion was developed for the case of small number of frequencies, which was used with an additional assumption of smoothness of the functions. The results for isothermal sound speed $u = p/\rho$, where p is a pressure, is shown in Fig.4.

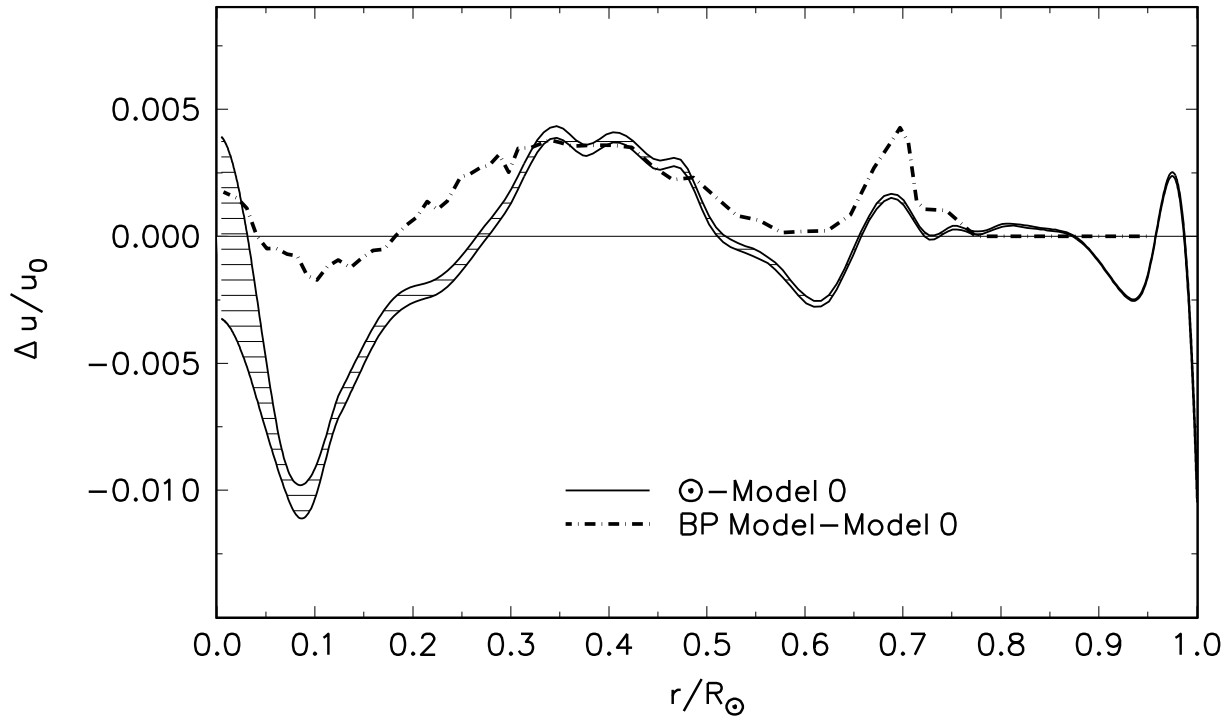


Fig.4 (from Dziembowski 1996). Isothermal sound speed ($u = p/\rho$) profile compared with the reference model of the author and with the SSM by Bahcall and Pinsonneault 1995. Shown is deflection of the sound speed Δu from the calculated value.

One can observe from Fig.4 that increasing of the deflections towards the inner core is changed for better agreement at smaller distances. Apart from the reference model 0 of the authors, this conclusion is valid also for the Bahcall-Pinsonneault (1995) model (the dash-dotted curve). However, the uncertainties of this result are rather large (Degl'Innocenti et al 1997a).

The excellent agreement of the Bahcall and Pinsonneault (1995) model with acoustic data in the inner core can be seen from analysis by Bahcall et al (1997). At $r/R \leq 0.2$ the agreement is better than 0.2%.

What is the status of the SSMs in the light of their confirmation by seismic data?

The accuracy of the SSM predictions better than 1% is actually more than is needed now for the calculations of solar-neutrino fluxes, because of two reasons. First, the uncertainties in the cross-sections are much larger. Second, the solar-neutrino deficit is most probably a result of neutrino oscillations, and the parameters of these oscillations must be in the end measured directly.

On the other hand the SSMs are confirmed by seismic observations only by two physical quantities: $\rho(r)$ and $c_s(r)$, or $p(r)$. Could it be that the other parameters important for calculations of solar-neutrino fluxes, e.g. temperature $T(r)$ and chemical composition $Y(r)$, $Z(r)$ etc, are given by the SSMs incorrectly? This question was raised by many people.

One may argue that this is unnatural possibility (see also Bahcall et al 1997). The adiabatic sound speed in fully ionized inner core, $c = \sqrt{\gamma RT/\mu}$, where μ is a molecular weight, and therefore one has for the small variations

$$\delta c/c = (1/2)(\delta T/T - \delta \mu/\mu). \quad (3)$$

In the SSMs all three values in Eq.(3) are close to each other. One can probably assume accidental fine-tuning (the compensation of large values in the rh-side of Eq.(3)) at some particular distance r , but it is hard to imagine a model with such compensation at all r .

In principle, the temperature can be directly measured by the width of the ${}^7\text{Be}$ -neutrino line (Bahcall 1993), but the energy resolution needed ($\sim 10^{-3}$) leaves this problem for the future technique.

One should not consider helioseismology just as auxiliary tool for solar neutrino physics. Its main task is to explore the finer structure of the sun than it is needed for the sake of the solar-neutrino physics. The seismic measurements give us clear indications to some phenomena not described by the SSMs. One can see in Fig.2 statistically very significant peculiarities at $r/R \sim 0.2$ and $r/T \sim 0.7$. The density profile (Fig.3) also exhibits the jump at $r/R \sim 0.7$, as well as small but regular deflection from the SSM density profile. It is interesting to note that both abovementioned irregularities occurs at distances where the SSMs predict the large composition gradients (Christensen-Dalsgaard 1996b). It can result in the mixing, which naturally produces (through the change of molecular weight) irregularities in the sound speed profile seen in Fig.2. However, the large mixing, which could affect the solar-neutrino fluxes, are ruled out (Bahcall et al 1997).

The SSMs are based on the following basic assumptions (see Bahcall 1989, Castellani et al 1997):

(i) The solar energy is generated by nuclear reactions (the calculations show that 98% of the energy is supplied by the pp -chain and 2% by the CNO-cycle).

(ii) The sun evolves in hydrostatic equilibrium, with gravitational attraction balanced by the pressure. The equation of state, which is employed to calculate the pressure, includes many fine effects, and probably can be considered as reliable. Instabilities are assumed not to be present. The effects due to sun rotation are neglected.

(iii) The energy transport is radiative in the solar core and convective outside it. Convection is treated according to rather simplified mixing-length theory (Christensen-Dalsgaard 1996a). The collective plasma effects (Tsytovich et al 1995) are neglected for radiative opacity.

(iii) When the sun first entered the Main Sequence, it was highly convective and therefore uniform in composition. It implies that the present chemical composition of its surface is the same as the initial chemical composition of the sun.

(iv) The diffusion of heavy elements and gravitational settling are included in the calculations: the heavy nuclei (He and heavier elements) diffuse to the center, due to excessive gravitational force, faster than hydrogen.

The model of the sun is evolved until it reaches the present luminosity. The calculated solar radius and age are in agreement with the observations. The most uncertain input parameters in these calculations are heavy element abundancies and calculated opacities.

There are several minor effects which should be included now in the solar models, due to small discrepancies of the SSMs with seismic data. Several kinds of instabilities can result in the small mixings. Most widely discussed is one, driven by low n and l g -mode oscillations, as was suggested first by Dilke and Gough (1972). Additional mixing can be caused by rotationally induced instabilities. Some mixing can occur beneath the convection zone. For the discussion of several effects of "non-standard" physics see Turck-Chieze et al (1993).

Can neutrino fluxes be calculated directly from seismic data? Apparently not, because for such calculations one must know the profile of chemical composition, which is given by some model of solar evolution. Ricci et al (1997) suggested an approach in which solar-neutrino fluxes are directly constrained by helioseismic data. This approach is not model-independent, but a wider class of models in comparison with the SSMs are considered. These models are based on the same equilibrium and evolution equations as the SSMs, but they allow the arbitrary choice of some input parameters. The correct models are chosen in the end due to seismic constraints. These models are called Helioseismically-Constrained Solar Models (HCSM). The most troublesome parameters of the SSMs are radiative opacity κ and the fraction of heavy elements Z/X , with relatively large errors. In the HCSM the arbitrary values of these parameters are used. As seismic "observables" three independent physical quantities, determined most accurately by seismic observations, are used, namely, the photospheric helium abundance, Y_{ph} , the depth of convective envelope, R_b , and the density, ρ_b , at the bottom of convective envelope. The central temperature calculated in this model is

$$T_{HCSM} = 1.58 \times 10^7 K \quad (4)$$

If all errors involved in the calculations are summed quadratically, the uncertainties in temperature determination is $(\Delta T/T)_{HCSM} = \pm 0.5\%$, to be compared with the similarly estimated uncertainties in the SSMs $(\Delta T/T)_{SSM} = \pm 1.7\%$. However, in the results cited below, we use more cautious (though less reasonable) approach, when all errors involved are summed up linearly. In this case we have $(\Delta T/T)_{HCSM} = \pm 1.4\%$ and $(\Delta T/T)_{SSM} = \pm 2.7\%$.

Neutrino fluxes as calculated in several SSMs and the HCSM are given in Table 3., where BP95 refers to Bahcall and Pinsonneault (1995), FR96 and FR97 - to Degl'Innocenti et al (1997b), and JCD - to model S of Christensen-Dalsgaard et al (1996c). Not surprisingly, the HCSM predicts the neutrino fluxes in agreement with the SSMs, but with reduced errors.

Note, that even when we sum errors linearly (the first errors in column HCSM), they are still

Table 3: Predictions for neutrino fluxes and signals in the Cl and Ga detectors from the SSM and the HCSM. Uncertainties corresponding to $(\Delta T/T)_{HCSM} = \pm 1.4\%$ are shown (first error) together with those from nuclear cross sections (second error).

		SSM				HCSM
		BP95	FR97	FR96	JCD	
Φ_{Be}	$[10^9/\text{cm}^2/\text{s}]$	5.15	4.49	4.58	4.94	$4.81 \pm 0.53 \pm 0.59$
Φ_B	$[10^6/\text{cm}^2/\text{s}]$	6.62	5.16	5.28	5.87	$5.96 \pm 1.49 \pm 1.93$
Cl	[SNU]	9.3	7.3	7.5	8.2	$8.4 \pm 1.9 \pm 2.2$
Ga	[SNU]	137	128	129	132	$133 \pm 11 \pm 8$

less than the errors from nuclear cross-sections (the second error in the same column). The

contradiction of these predictions with the observed fluxes (Table 1) demonstrates the conflict between helioseismologically-constrained solar models and the standard neutrino.

4. NUCLEAR REACTIONS

Uncertainties in cross-sections of nuclear reactions cannot solve the SNP (Berezinsky et al 1996), but these uncertainties cause now the largest errors in the prediction of solar-neutrino fluxes. The status of nuclear reactions in the sun was recently reviewed by Castellani et al (1997). The new, very recent progress is connected with measurements of ${}^3\text{He} + {}^3\text{He}$ cross-section in the LUNA experiment at Gran Sasso and with detailed calculations of the plasma effects in nuclear reactions (Gruzinov and Bahcall 1997 and Brown and Sawyer 1997). These effects include in particular electron screening and related problem of electron capture by ${}^7\text{Be}$. These calculations confirm the previous results within accuracy needed for calculations of the solar-neutrino fluxes.

As was already mentioned in Introduction, the cross-section of ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$ reaction could be of crucial importance for the SNP. If this cross-section were large at the energy of the Gamow peak ($\sim 20 \text{ keV}$), e.g. due to presence of the narrow resonance at this energy, the production of ${}^4\text{He}$ in the sun would go mainly through the chain I (see Table 2), and thus production of beryllium and boron neutrinos would be suppressed. The cross-section of this reaction as a function of energy is shown in Fig.5 (Arpesella et al 1996). The recent LUNA data (filled circles) correspond to the solar Gamow peak and coincide well with extrapolation from higher energies in case of screening.

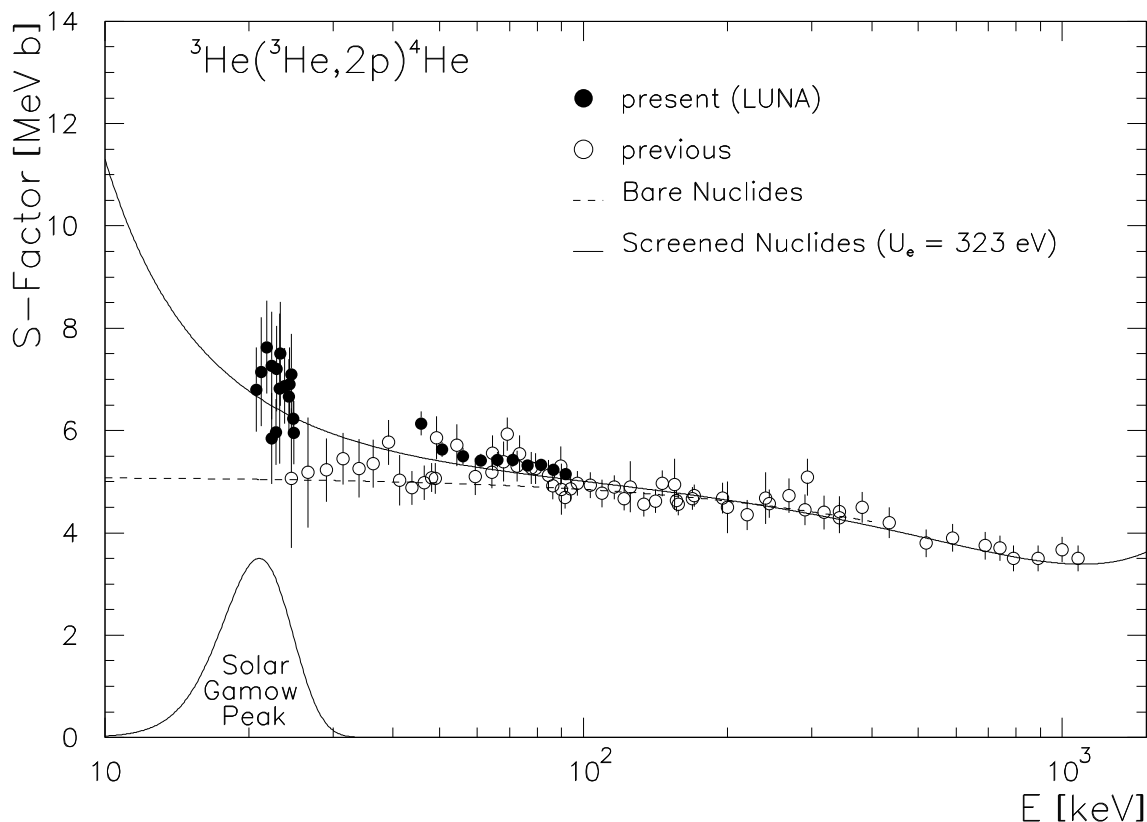


Fig.5 (from Arpesella et al 1996). The compilation of astrophysical factors for ${}^3\text{He} + {}^3\text{He}$ cross-section. The LUNA data are shown by filled circles at the energy of the Gamow peak.

The most important reaction for boron neutrino production $p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$ has the largest uncertainties in the cross-section (see Castellani et al 1997). Most authors use for model calculations the astrophysical factor at the energy of the Gamov peak $S_{17}(0) = 22.4 \pm 2.1 \text{ eVb}$, while much lower value, $16.7 \pm 3.2 \text{ eVb}$ is obtained from Coulomb dissociation of ${}^8\text{B}$ -nuclei.

The measurement of this cross-section at energy down to $E_{cm} = 30 \text{ keV}$ is planned for the second phase (1998 - 2002) of the LUNA experiment. It is one of the reactions, which will be measured at the second phase. The others are $p + D \rightarrow {}^3\text{He} + \gamma$, $D + {}^3\text{He} \rightarrow {}^4\text{He} + p$, ${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$, and $p + {}^{14}\text{N} \rightarrow {}^{15}\text{O} + \gamma$ etc.

5. ELEMENTARY-PARTICLE SOLUTIONS

There are three elementary-particle solutions which can explain the results of solar-neutrino experiments: MSW effect (Mikheev and Smirnov 1986a, Wolfenstein 1978), vacuum oscillations (Pontecorvo 1957) and Resonant Spin-Flavor Precession, RSFP (Akhmedov 1988, Lim and Marciano 1988). In all these solutions electron neutrinos, born in the sun, are converted into other neutrino states (muon neutrinos, sterile neutrinos or muon antineutrinos) and thus do not interact in the neutrino detectors, or interact weakly through neutral current effects (e.g. $\nu_\mu + e \rightarrow \nu_\mu + e$). The survival probability for ν_e depends on neutrino energy and actually this property allows to explain the different neutrino deficit in the solar-neutrino experiments. The maximum suppression must approximately correspond to the energy of beryllium neutrinos.

In case of the MSW and RSFP, the conversion of ν_e into another neutrino flavor occurs *inside* the sun due to effects of matter oscillation. Effect of vacuum oscillation takes place on the way from the sun to earth.

All three solutions are characterized by the difference of neutrino masses squared, Δm^2 and by mixing angle, θ between two neutrino mass states ν_1 and ν_2 , which form neutrino flavor state, e.g. ν_e or ν_μ . The energy shape of suppression curve for neutrino fluxes is determined by the pair of values $(\Delta m^2, \sin^2 2\theta)$ and therefore the different points in $\Delta m^2 - \sin^2 2\theta$ plane give the different predictions for the signal in the neutrino detectors. It is not trivial that there are regions in this plane, which explain the results of all four solar-neutrino experiments. It is easy to understand that for the different regions the distortion of the produced neutrino *spectrum* is different.

Let us start with vacuum oscillations.

In case of two neutrino flavors, ν_e and ν_μ are superposition of two mass states ν_1 and ν_2 with masses m_1 and m_2 , respectively:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \quad (5)$$

$$|\nu_\mu\rangle = \cos\theta|\nu_2\rangle - \sin\theta|\nu_1\rangle \quad (6)$$

Here and everywhere else θ is the vacuum mixing angle. As a result of β decay in the sun ν_e -neutrino with a fixed energy E is produced, and therefore the states ν_1 and ν_2 have the different momenta $p_1 \approx E - m_1^2/2E$ and $p_2 \approx E - m_2^2/2E$. At the distance r from the source the states ν_1 and ν_2 obtain different phases $\exp(ip_1 r)$ and $\exp(ip_2 r)$. Thus, ν_e from Eq.(5) becomes

$$|\nu(r)\rangle = \exp(ip_1 r) \cos\theta|\nu_1\rangle + \exp(ip_2 r) \sin\theta|\nu_2\rangle, \quad (7)$$

which now has admixture of ν_μ . The probability, that performing an experiment one finds this neutrino as the muon neutrino is easy to calculate as

$$P_{\nu_e \rightarrow \nu_\mu}(r) = |\langle \nu_\mu | \nu(r) \rangle|^2 = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} r\right), \quad (8)$$

where $\Delta m^2 = m_1^2 - m_2^2$ and $l_v = 4\pi E/\Delta m^2$ is the vacuum oscillation length.

For the recent detailed discussion of vacuum oscillation solution for the SNP see Krastev and Petcov (1996) and Hata and Langacker (1997).

The regions in $\Delta m^2 - \sin^2 2\theta$ plane which explain all observational data and include the constraint due the Kamiokande energy spectrum, are shown in Fig.6 (Hata and Langacker 1997). One can see that only large-angle solutions are allowed, with very small $\Delta m^2 \approx (5 - 8) \cdot 10^{-10} \text{ eV}^2$.

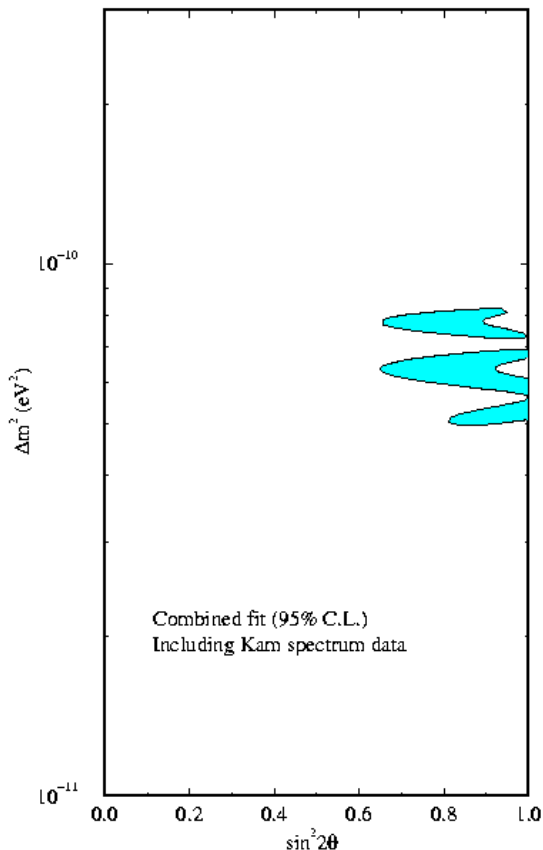


Fig.6 (from Hata and Langacker 1997). Vacuum oscillations: The regions allowed for explanation of all solar-neutrino data including the Kamiokande energy spectrum.

The MSW effect describes the matter enhanced oscillations. It has a resonant character and for energies of neutrinos at interest typically occurs in the narrow layer, $\Delta R \sim 0.01 R_\odot$, at the distance $R \sim 0.1 R_\odot$ from the center of the sun.

One can give the qualitative explanation of the adiabatic MSW effect.

Let us consider the case when electron neutrino in vacuum is almost the light state ν_1 , while the muon neutrino is almost the heavy state ν_2 . Let both neutrinos have the same momentum $p \gg m$. Then the energy of each neutrino is $E_1 = p + m_1^2/2p + V_1$ and $E_2 = p + m_2^2/2p + V_2$, where V_1 and V_2 are matter-induced potential energies of neutrinos, which are determined by scattering of neutrinos in matter. The difference of neutrino energies at equal momentum is $\Delta E = \Delta m^2/2p + W(r)$, where $W(r) = V_2 - V_1$ is the difference of the potentials, determined by the different scattering of ν_e and ν_μ on electrons: in the ν_e case it is provided by charged and neutral currents, while for ν_μ - only by the neutral current. The explicit calculations give

$W(r) = -\sqrt{2}G_F n_e(r)$, where G_F is the Fermi constant and $n_e(r)$ is the density of electrons inside the sun. Therefore, we obtain

$$\Delta E = \Delta m^2/2p - \sqrt{2}G_F n_e(r).$$

In more adequate treatment, the difference of the diagonal terms of the Hamiltonian plays the role of ΔE , and one has

$$\Delta H = \cos 2\theta \Delta m^2/2p - \sqrt{2}G_F n_e(r) \quad (9)$$

Locally, ΔE (or ΔH) is interpreted as due to difference in neutrino masses. Then at $r \rightarrow \infty$ when $n_e = 0$, $\Delta E > 0$, i.e. muon neutrino is heavier than electron neutrino. At $r \rightarrow 0$, when second term in rhs of Eq.(9) dominates, electron neutrino is heavier. If density $n_e(r)$ changes slowly, adiabatic approximation holds, and electron neutrino propagating from the solar core outside, remain on the heavy state trajectory. It means that it leaves the sun as muon neutrino. This conversion mainly occurs, when $\Delta H \rightarrow 0$. According to Eq.(9) it determines the critical density n_c , when conversion has the resonant character:

$$2\sqrt{2}G_F p n_c = \Delta m^2 \cos 2\theta_v \quad (10)$$

The present status of the MSW solution is illustrated by Fig.7 (Bahcall and Krastev 1997). The SSM used in the calculations is the one by Bahcall and Pinsonneault (1995). At 95%CL there are two allowed regions, given by the *small angle* solution around the point of local χ^2 minimum $\Delta m^2 = 5 \cdot 10^{-6} \text{ eV}^2$ and $\sin^2 2\theta = 9 \cdot 10^{-3}$, and the *large-angle* solution with the χ^2 -min point $\Delta m^2 = 1.2 \cdot 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta = 0.6$. At 99% CL the third large angle solution appears.

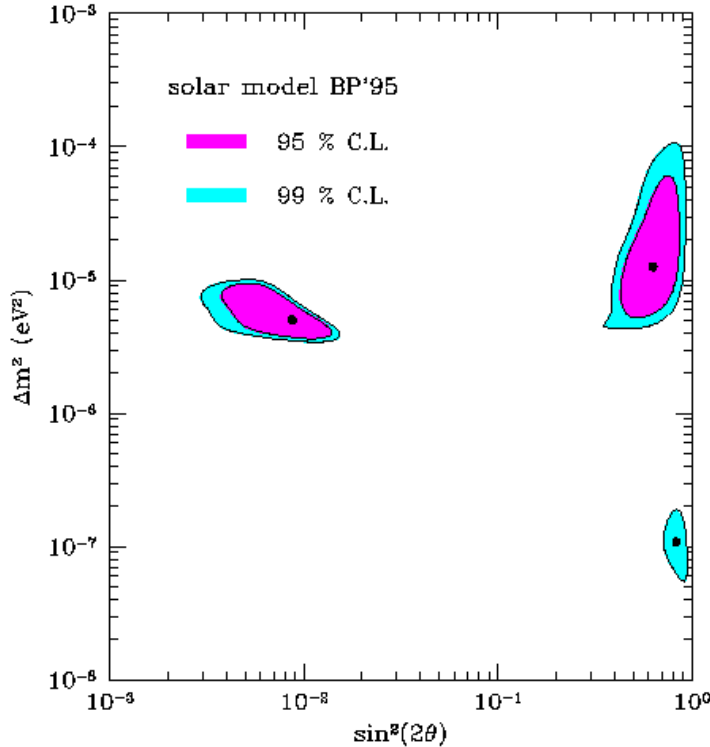


Fig.7 (from Bahcall and Krastev 1997). MSW conversion: The regions allowed for explanation of all solar-neutrino data.

The suppression curves, i.e. the survival probability $P(\nu_e \rightarrow \nu_e)$ as a function of neutrino energy, are given in Fig.8 (Berezinsky 1995) for the small angle MSW solution with the different $\sin^2 2\theta$. One can see that for the central point of the solution with $\sin^2 2\theta = 9 \cdot 10^{-3}$ the spectrum is very strongly distorted in the energy region $6 - 14 \text{ MeV}$, where the measurements of SuperKamiokande and SNO will be soon available. However, as was noted by Krastev and Smirnov (1994) and by Berezinsky et al (1994) (see Hata and Langacker 1997, Fig.18, for recent calculations) the small reduction of calculated boron-neutrino flux, for example due to diminishing S_{17} , shifts the small-mixing solution towards the smaller mixing angles. In particular the value $\sin^2 2\theta \approx 1 \cdot 10^{-3}$ is possible due to present uncertainties in S_{17} . In this case one can see from Fig.8 that for the energies $E \geq 6 \text{ MeV}$, accessible for SuperKamiokande and SNO, the distortion of energy spectrum is small.

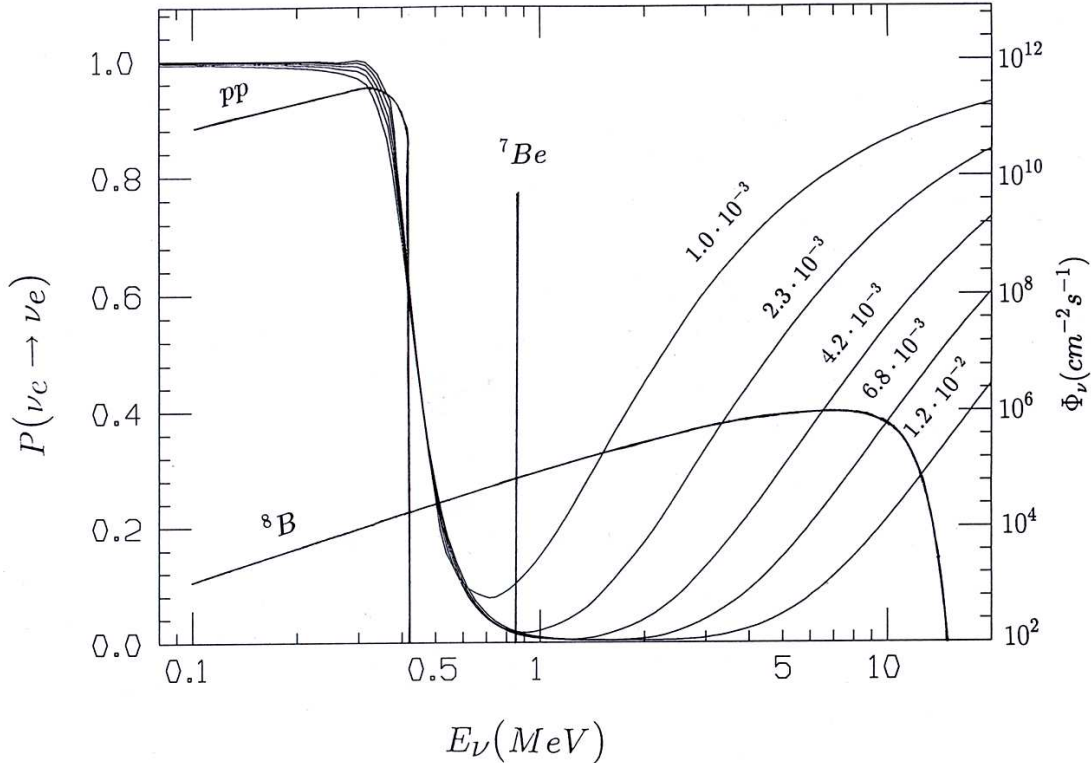


Fig. 8 (from Berezinsky 1995). The suppression factor $P(\nu_e \rightarrow \nu_e)$ for the MSW small-angle solution for different values of $\sin^2 2\theta$ (indicated on the curves). On the right vertical axis the neutrino fluxes are shown.

The Resonant Spin-Flavor Precession (RSFP) describes two physical effects working simultaneously: the spin-flavor precession, when neutrino spin precesses around magnetic field, changing simultaneously neutrino flavor, and the resonant, density-dependent effect, which produces difference in potential energy of neutrinos with different flavors (a la the MSW effect). This complicated transition occurs in the external magnetic field due to presence of non-diagonal neutrino magnetic moments. The RSFP was recognized simultaneously by Akhmedov (1988) and Lim and Marciano (1988). For excellent recent review see Akhmedov (1997).

This theory had a predecessor. The neutrino spin precession was studied by Voloshin, Vysotsky and Okun (1986). The precession of neutrino magnetic moment around magnetic field converts left electron neutrino ν_{eL} into sterile right component ν_{eR} , suppressing thus ν_e -flux. However, the suppression effect in this case is energy-independent and thus contradicts to the recent solar-neutrino data. Voloshin, Vysotsky, Okun (1986) and Barbieri and Fiorentini (1988)

included the matter effects in the spin precession, and Schechter and Valle (1981) discovered spin-flavor precession. The latest results of solar-neutrino experiments can be explained only by the RSFP, because only this type of precession give the energy-dependent suppression factor.

In case of Majorana neutrino the RSFP induces the transition ν_{eL} to $\bar{\nu}_{\mu R}$, i.e. to another active neutrino component (it can scatter off the electron). The suppression factor was calculated e.g. by Akhmedov et al (1993) and by Lim and Nunokawa (1995). It has different shape in comparison with the one for the MSW or vacuum-oscillation solution. At large neutrino energies it tends to 1/2, compared with 1 for vacuum oscillations and the MSW. It means that the total suppression of SuperKamiokande signal is always larger than in the case of the MSW solution. It looks like a difficulty for this solution. However, Lim and Nunokawa (1995) found that the RSFP can explain all solar-neutrino data for the following range of parameters: neutrino magnetic moment $\mu = 1 \cdot 10^{-11} \mu_B$, magnetic field in the range 25 – 130 kG and Δm^2 in the range $7 \cdot 10^{-9} - 2 \cdot 10^{-7} \text{ eV}^2$. The neutrino magnetic moment $\mu = 1 \cdot 10^{-11} \mu_B$ is in conflict with the observations of the helium flashes of the red giants ($\mu < 3 \cdot 10^{-12} \mu_B$, Raffelt (1990).

6. SIGNATURES OF ELEMENTARY-PARTICLE SOLUTIONS

The common signature of all three elementary-particle solutions is distortion of neutrino energy spectrum. It seems very unlikely that spectrum distortion will not be found in SuperKamiokande and SNO during the next 3-5 years. The energy spectrum will be precisely measured in the future experiments, ICARUS (ICARUS Collaboration 1994) and HELLAZ (Ypsilantis 1992 and references therein). Another common feature of all three solutions is that maximum of suppression curve corresponds to the energy of ${}^7\text{Be}$ neutrinos. Borexino at Gran Sasso will be able to observe this effect (see Bellini 1996 and references therein). It is worth to note that Borexino will detect not only ν_e -flux, but also another final state of oscillation, if it is active (e.g. $\nu_\mu, \bar{\nu}_\mu$ etc). The recent suggestion by Raghavan (1997) of measuring fluxes of sub-MeV ν_e -neutrinos due to inverse beta decays on ${}^{176}\text{Yb}$, ${}^{160}\text{Gd}$ and ${}^{82}\text{Se}$ looks like an excellent supplementary experiment for the Borexino.

It is much more difficult to distinguish experimentally between the three abovementioned solutions. The suppression curves for the MSW and vacuum oscillation solutions are similar in all cases and in some cases they are almost identical. There are some additional effects which can distort the shape of suppression factor (e.g. the density fluctuations in case of the MSW effect - see Nunokawa et al 1996). What is more important, the small difference in the spectral shape cannot be considered as a final proof of discovery, for example, the MSW effect. It can be taken as an indication, but not more.

Fortunately, there are clear signatures for each solution.

For MSW-solution this signature is the day-night effect, caused by neutrino matter-oscillations in the earth (Mikheev and Smirnov 1986b, 1986c and references therein). The neutrino spectrum from the sun will be additionally distorted in the *night* by the MSW effect in the earth. The effect is two-fold: ν_e -neutrinos are converted with some probability into ν_μ (we limit ourselves by these two flavors only), and ν_μ , produced in the sun due to the MSW effect, will be partly regenerated in the earth back to ν_e . These effects depend on the part of the earth neutrinos cross. The effect is stronger when neutrinos cross the earth core, and weaker when they pass through the mantle only. The detailed calculations for the day-night effect relevant for superkamiokande were recently performed by Maris and Petcov (1997) (see also the references for the early calculations there). The value of practical use, which they consider is

$$A_{D-N}^s = 2 \frac{R^s - R^D}{R^s + R^D}, \quad (11)$$

where R^s is the counting rate in SuperKamiokande for the neutrino events with the energies of the recoil electrons higher than 5 MeV in the night time, when neutrino passes through the

core ($s = c$) or through the mantle only ($s = m$) and R^D is the counting rate in the day time. Therefore, A_{D-N}^s is the asymmetry related to the counting rate of neutrinos crossing the earth core or mantle only. The calculations are performed for the wide range of Δm^2 and $\sin^2 2\theta$, but the most interest should be given to the values corresponding to the small-angle and large-angle MSW solutions. For most interesting small-angle solution, the asymmetry is much stronger for the core case. The asymmetry here varies between 1% and 20%, but in some cases it is less than 1% and even zero. One should remember that statistics of the core sample is low and long observations are needed to discover 1% asymmetry.

The anomalous seasonal variation of neutrino flux is a signature of *vacuum oscillations*. The distance between the sun and earth changes with time as

$$r(t) = r_0(1 + \epsilon \cos 2\pi t/T), \quad (12)$$

where $\epsilon = 0.0167$ is the ellipticity of the earth orbit and $r_0 = 1.5 \cdot 10^{13} \text{ cm}$ is the mean distance between the sun and earth. Thus, the geometrical seasonal variation in neutrino fluxes is about 7% between the maximum and minimum.

The time variation of distance between the sun and earth, results in the time dependent conversion $\nu_e \rightarrow \nu_\mu$, as one can see from Eq.(8), where r now is a function of time. The time variation of solar neutrino flux was studied in the detail by Krastev and Petkov (1994) (for the recent calculations see Smirnov 1997). The strongest seasonal variation was found for ${}^7\text{Be}$ and pep-neutrinos. These variations much exceed the geometrical one, and they will be unmistakably tested by Borexino. The seasonal variations of boron neutrino flux due to vacuum oscillations is comparable with the geometrical variations. For some allowed regions ($\Delta m^2, \sin^2 2\theta$) they compensate the geometrical variations, for others they increase them by factor of 2. The variation of the flux correlates with spectrum distortion (Smirnov 1997). SuperKamiokande can discover the flux variation caused by "central" vacuum solution during 5 years of observations (Y.Suzuki, private communication).

The signature of the RSFP-solution is time variation of solar neutrino flux with the period of variation of magnetic field in the sun.

The magnetic field responsible for the RSFP is most probably the toroidal magnetic field at the bottom of convective zone. The magnetic activity of the sun exhibits quasi-periodic time variations with the mean period 11 *yr*. Taking into account changing of magnetic polarity, one can argue for 22 *yr* as a basic period for large-scale magnetic field. This periodicity is thought to be originated due to toroidal field, generated in so-called *overshoot layer* by dynamo mechanism and located near the bottom of convective zone. Theoretically, magnetic field there can reach 100 *kG*. This field rises through convective zone to the surface of the sun.

The RSFP-effect for beryllium and boron neutrinos takes place in the convective zone, while for pp-neutrinos in the radiative zone, where magnetic field is known worse. As was mentioned before, the RSFP solution needs magnetic field in the convective zone in the range 25 – 130 *kG*, which is allowed by the theoretical concept described above.

The time variation of magnetic field results in the framework of the RSFP scenario in the variation of neutrino flux with the same period. The variation of neutrino flux depends on neutrino energy. This dependence one can see from energy dependence of the suppression factor. It is straightforward that variation is stronger for energies, where suppression is stronger. Therefore, pp-neutrinos should not vary with time, while the boron neutrinos and especially ${}^7\text{Be}$ -neutrinos must expose time variation.

The straightforward analysis of neutrino signals in all four solar-neutrino detectors does not reveal statistically significant time variations. In particular, it is true for the Homestake data

(Lissia 1996a and 1996b). However, when correlations with surface solar phenomena such as surface magnetic field, solar spots, green line and solar wind are included in the analysis, the 11 year time variations of neutrino signal in the Homestake data become statistically significant, at least up to 1990 (for a comprehensive review see Stanev 199a and 1996b). This situation reminds me the epic of Cyg X-3, from which the direct signal in high energy gamma-rays in all cases, except the Kiel detector, was not seen, while the correlation with 4.8 h periodical X-ray flux, gave the statistically significant signal in many detectors.

One of the objections against the time-variable signal in the Homestake detector is the absence of such dependence in the Kamiokande and gallium detectors. This objection actually is not correct. The time variation effect in the Kamiokande detector, in case of the RSFP, must be weaker than in the Homestake detector. First, the Homestake detector has significant, 13%, contribution from strongly variable flux of ${}^7\text{Be}$ -neutrinos. Secondly, ν_μ -neutrinos from oscillation of ν_e give contribution to the Kamiokande signal, but not to the Homestake signal (Akhmedov 1997).

The time variation of the signal should exist for both gallium experiments (due to 28% contribution of the beryllium-neutrino flux) and for SuperKamiokande, because even at highest energies the boron neutrino flux under the RSFP is suppressed by factor not smaller than 2. However, this dependence is expected to be weaker than in the Homestake detector.

The Borexino detector, observing directly beryllium neutrinos, will reliably test the above-mentioned time variation.

Another possible signature of the RSFP is production of $\bar{\nu}_e$ -neutrinos. They appear due to vacuum oscillation of $\bar{\nu}_\mu$ on the way from the sun to earth (see Akhmedov 1997 and the references therein). As one can see from Eq.(8) the amplitude of this oscillation is proportional to $\sin^2 2\theta$. For a typical RSFP solution this value is 0.1-0.2 and thus the $\bar{\nu}_e$ -flux with the energy of beryllium neutrinos will be easily detectable in the Borexino.

7. CONCLUSIONS

The Solar Neutrino Problem (SNP) is a deficit of neutrino fluxes detected in all four solar-neutrino experiments, as compared with the SSMs predictions. Not related to the SSMs, there is a conflict between data of neutrino experiments, which within astrophysical solution to the SNP (standard neutrino), results in unphysical zero beryllium neutrino flux.

This result was known for the last several years. The situation has changed now when the predictions of the SSMs (sound speed and density radial profiles) are confirmed by the precise helioseismic measurements for all radial distance at interest. The recent measurements of cross-section ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$ at the energy of the solar Gamow peak in the LUNA experiment at Gran Sasso, confirmed further the predictions of solar-neutrino fluxes by the SSMs. It is difficult to doubt now that the SSMs give the adequate description of the sun interior. The conflict between the observed neutrino flux and the predictions of seismically confirmed SSMs can be considered as the strongest argument against the standard neutrino.

The SSMs being sufficient for prediction of neutrino fluxes are unable to describe the small irregularities in the observed radial profiles of density and sound speed. They imply some physical processes not included in the SSMs, which most probably result in the small mixing inside the sun not much relevant to the prediction of neutrino fluxes.

30-40 years ago we thought that neutrinos with their tremendous penetrating power give us the only way to look inside the sun. Now we see that helioseismology makes it more precisely, while the solar neutrino fluxes give us unique information about neutrino properties.

There are three elementary-particle solutions to the SNP: the MSW, vacuum oscillations and the Resonant Spin-Flavor Precession (RSFP). In all three solutions the neutrino is not standard, i.e. it is not described by the SM of EW interactions. It is massive, the lepton numbers are not conserved and the mass matrix is not diagonal in the flavor representation.

The elementary particle solutions successfully describe the results of all four solar-neutrino experiments, because the suppression factors of neutrino fluxes are energy dependent (the beryllium neutrino flux is most strongly suppressed). It immediately results in the common signature of all three solutions: the measured boron-neutrino energy spectrum must be distorted as compared with the 8B -decay neutrino spectrum. It looks most probable that SuperKamiokande and SNO will discover the distortion of the spectrum in the near future. The additional signature could be the anomalous neutral-current scattering (through neutron detection) in SNO, and measurement of Be -neutrino flux in Borexino.

To distinguish between these three solutions is much more difficult task.

The signature of the MSW-solution is the day-night effect, which can be observed by SuperKamiokande. The value of this effect can vary between 1% and 20%, being zero for some values of $(\Delta m^2, \sin^2 2\theta)$. In all cases, the effect is strongest when neutrinos cross the earth core. It limits significantly statistics of observations.

The signature of the vacuum oscillations is a seasonal variation of neutrino flux, in addition to geometrical seasonal variation $1/r^2(t)$, where $r(t)$ is a time dependent distance between the earth and sun. These variations are very significant for beryllium neutrinos and can be reliably tested by Borexino.

The signature of the RSFP-solution is the 11 year periodicity of neutrino flux with the largest amplitude for beryllium neutrinos. Another signature is a considerable fraction of $\bar{\nu}_e$ neutrinos at the energy of beryllium neutrinos due to vacuum oscillation $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ on the way from the sun to earth. Both signatures can be reliably detected by Borexino.

The next generation detectors, ICARUS and HELLAZ, will provide us with much more detailed information about energies of neutrinos and arrival direction.

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